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Search for new light gauge bosons in Higgs boson decays to four-lepton final states in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the LHC

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This paper presents a search for Higgs bosons decaying to four leptons, either electrons or muons, via one or two light exotic gauge bosons Z_d , $H \rightarrow ZZ_d \rightarrow 4\ell$ or $H \rightarrow Z_d Z_d \rightarrow 4\ell$. The search was performed using pp collision data corresponding to an integrated luminosity of about 20 fb^{-1} at the center-of-mass energy of $\sqrt{s} = 8$ TeV recorded with the ATLAS detector at the Large Hadron Collider. The observed data are well described by the Standard Model prediction. Upper bounds on the branching ratio of $H \rightarrow ZZ_d \rightarrow 4\ell$ and on the kinetic mixing parameter between the Z_d and the Standard Model hypercharge gauge boson are set in the range $(1-9) \times 10^{-5}$ and $(4-17) \times 10^{-2}$ respectively, at 95% confidence level assuming the Standard Model branching ratio of $H \rightarrow ZZ^* \rightarrow 4\ell$, for Z_d masses between 15 and 55 GeV. Upper bounds on the effective mass mixing parameter between the Z and the Z_d are also set using the branching ratio limits in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search, and are in the range $(1.5-8.7) \times 10^{-4}$ for $15 < m_{Z_d} < 35$ GeV. Upper bounds on the branching ratio of $H \rightarrow Z_d Z_d \rightarrow 4\ell$ and on the Higgs portal coupling parameter, controlling the strength of the coupling of the Higgs boson to dark vector bosons are set in the range $(2-3) \times 10^{-5}$ and $(1-10) \times 10^{-4}$ respectively, at 95% confidence level assuming the Standard Model Higgs boson production cross sections, for Z_d masses between 15 and 60 GeV.

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I. INTRODUCTION

Hidden sector or dark sector states appear in many extensions to the Standard Model (SM) [1–10], to provide a candidate for the dark matter in the Universe [11] or to explain astrophysical observations of positron excesses [12–14]. A hidden or dark sector can be introduced with an additional $U(1)_d$ dark gauge symmetry [5–10].

In this paper, we present model-independent searches for dark sector states. We then interpret the results in benchmark models where the dark gauge symmetry is mediated by a dark vector boson Z_d . The dark sector could couple to the SM through kinetic mixing with the hypercharge gauge boson [15–17]. In this hypercharge portal scenario, the kinetic mixing parameter ϵ controls the coupling strength of the dark vector boson and SM particles. If, in addition, the $U(1)_d$ symmetry is broken by the introduction of a dark Higgs boson, then there could also be a mixing between the SM Higgs boson and the dark sector Higgs boson [5–10]. In this scenario, the Higgs portal coupling κ controls the strength of the Higgs coupling to dark vector bosons. The observed Higgs boson would then be the lighter partner of the new Higgs doublet, and could also decay via the dark sector. There is an additional Higgs portal scenario where

there could be a mass-mixing between the SM Z boson and Z_d [7,8]. In this scenario, the dark vector boson Z_d may couple to the SM Z boson with a coupling proportional to the mass mixing parameter δ .

The presence of the dark sector could be inferred either from deviations from the SM-predicted rates of Drell-Yan (DY) events or from Higgs boson decays through exotic intermediate states. Model-independent upper bounds, from electroweak constraints, on the kinetic mixing parameter of $\epsilon \leq 0.03$ are reported in Refs. [5,18,19] for dark vector boson masses between 1 and 200 GeV. Upper bounds on the kinetic mixing parameter based on searches for dilepton resonances, $pp \rightarrow Z_d \rightarrow \ell\ell$, below the Z -boson mass are found to be in the range of 0.005–0.020 for dark vector boson masses between 20 and 80 GeV [20]. The discovery of the Higgs boson [21–23] during Run 1 of the Large Hadron Collider (LHC) [24,25] opens a new and rich experimental program that includes the search for exotic decays $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow Z_d Z_d \rightarrow 4\ell$. This scenario is not entirely excluded by electroweak constraints [5–10,18,20]. The $H \rightarrow ZZ_d$ process probes the parameter space of ϵ and m_{Z_d} , or δ and m_{Z_d} , where m_{Z_d} is the mass of the dark vector boson, and the $H \rightarrow Z_d Z_d$ process covers the parameter space of κ and m_{Z_d} [5,6]. DY production, $pp \rightarrow Z_d \rightarrow \ell\ell$, offers the most promising discovery potential for dark vector bosons in the event of no mixing between the dark Higgs boson and the SM Higgs boson. The $H \rightarrow ZZ_d \rightarrow 4\ell$ process offers a discovery potential complementary to the DY process for $m_{Z_d} < m_Z$ [5,20]. Both of these would be needed to understand the properties

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of the dark vector boson [5]. If the dark Higgs boson mixes with the SM Higgs boson, the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ process would be important, probing the dark sector through the Higgs portal coupling [5,6].

This paper presents a search for Higgs bosons decaying to four leptons via one or two Z_d bosons using pp collision data at $\sqrt{s} = 8$ TeV collected at the CERN LHC with the ATLAS experiment. The search uses a data set corresponding to an integrated luminosity of 20.7 fb^{-1} with an uncertainty of 3.6% for $H \rightarrow ZZ_d \rightarrow 4\ell$ based on the luminosity calibration used in Refs. [26,27], and 20.3 fb^{-1} with an uncertainty of 2.8% for $H \rightarrow Z_d Z_d \rightarrow 4\ell$ based on a more recent calibration [28]. Same-flavor decays of the Z and Z_d bosons to electron and muon pairs are considered, giving the $4e$, $2e2\mu$, and 4μ final states. Final states including τ leptons are not considered in the $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow Z_d Z_d \rightarrow 4\ell$ decays. In the absence of a significant signal, upper bounds are set on the relative branching ratios $\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)/\text{BR}(H \rightarrow 4\ell)$ and $\text{BR}(H \rightarrow Z_d Z_d \rightarrow 4\ell)/\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)$ as functions of the mass of the dark vector boson m_{Z_d} . The branching ratio limits are used to set upper bounds on the kinetic mixing, mass mixing, and Higgs boson mixing parameters [5,6]. The search is restricted to the mass range where the Z_d from the decay of the Higgs boson is on-shell, i.e. $15 \text{ GeV} < m_{Z_d} < m_H/2$, where $m_H = 125 \text{ GeV}$. Dark vector boson masses below 15 GeV are not considered in the present search. Although the low-mass region is theoretically well motivated [7,8], the high p_T of the Z_d boson relative to its mass leads to signatures that are better studied in dedicated searches [29].

The paper is organized as follows. The ATLAS detector is briefly described in Sec. II. The signal and background modeling is summarized in Sec. III. The data set, triggers, and event reconstruction are presented in Sec. IV. Detailed descriptions of the searches are given in Secs. V and VI for $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow Z_d Z_d \rightarrow 4\ell$ processes, respectively. Finally, the concluding remarks are presented in Sec. VII.

II. EXPERIMENTAL SETUP

The ATLAS detector [30] covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. The ATLAS inner detector (ID) has full coverage¹ in the azimuthal angle ϕ and covers the pseudorapidity range $|\eta| < 2.5$. It consists

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. The azimuthal angle ϕ is measured around the beam axis, and the polar angle θ is measured with respect to the z axis. ATLAS defines transverse energy $E_T = E \sin \theta$, transverse momentum $p_T = p \sin \theta$, and pseudorapidity $\eta = -\ln[\tan(\theta/2)]$.

of a silicon pixel detector, a silicon microstrip detector, and a straw-tube tracker that also measures transition radiation for particle identification, all immersed in a 2 T axial magnetic field produced by a superconducting solenoid.

High-granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent energy and position resolution, cover the pseudorapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a scintillator-tile calorimeter, consisting of a large barrel and two smaller extended barrel cylinders, one on either side of the central barrel. The LAr endcap ($1.5 < |\eta| < 3.2$) and forward sampling calorimeters ($3.1 < |\eta| < 4.9$) provide electromagnetic and hadronic energy measurements.

The muon spectrometer (MS) measures the deflection of muon trajectories with $|\eta| < 2.7$ in a toroidal magnetic field. Over most of the η -range, precision measurement of the track coordinates in the principal bending direction of the magnetic field is provided by monitored drift tubes. Cathode strip chambers are used in the innermost layer for $2.0 < |\eta| < 2.7$. The muon spectrometer is also instrumented with dedicated trigger chambers, resistive-plate chambers in the barrel and thin-gap chambers in the end-cap, covering $|\eta| < 2.4$.

The data are collected using an online three-level trigger system [31] that selects events of interest and reduces the event rate from several MHz to about 400 Hz for recording and offline processing.

III. MONTE CARLO SIMULATION

Samples of Higgs boson production in the gluon fusion (ggF) mode, with $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow Z_d Z_d \rightarrow 4\ell$, are generated for $m_H = 125 \text{ GeV}$ and $15 < m_{Z_d} < 60 \text{ GeV}$ (in 5 GeV steps) in MADGRAPH5 [32] with CTEQ6L1 [33] parton distribution functions (PDF) using the hidden Abelian Higgs model (HAHM) as a benchmark signal model [5,9,10]. PYTHIA8 [34,35] and PHOTOS [36–38] are used to take into account parton showering, hadronization, and initial- and final-state radiation.

The background processes considered in the $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow Z_d Z_d \rightarrow 4\ell$ searches follow those used in the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements [39], and consist of the following:

- (i) Higgs boson production via the SM ggF, VBF (vector boson fusion), WH , ZH , and $t\bar{t}H$ processes with $H \rightarrow ZZ^* \rightarrow 4\ell$ final states. In the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search, these background processes are normalized with the theoretical cross sections, where the Higgs boson production cross sections and decay branching ratios, as well as their uncertainties, are taken from Refs. [40,41]. In the $H \rightarrow ZZ_d \rightarrow 4\ell$ search, the normalization of $H \rightarrow 4\ell$ is determined from data. The cross section for the ggF process has been calculated to next-to-leading order (NLO) [42–44] and next-to-next-to-leading order (NNLO) [45–47] in QCD. In addition, QCD

soft-gluon resummations calculated in the next-to-next-to-leading-logarithmic (NNLL) approximation are applied for the ggF process [48]. NLO electroweak (EW) radiative corrections are also applied [49,50]. These results are compiled in Refs. [51–53] assuming factorization between QCD and EW corrections. For the VBF process, full QCD and EW corrections up to NLO [54–56] and approximate NNLO QCD [57] corrections are used to calculate the cross section. The cross sections for the associated WH and ZH production processes are calculated at NLO [58] and at NNLO [59] in QCD, and NLO EW radiative corrections are applied [60]. The cross section for associated Higgs boson production with a $t\bar{t}$ pair is calculated at NLO in QCD [61–64]. The SM ggF and VBF processes producing $H \rightarrow ZZ^* \rightarrow 4\ell$ backgrounds are modeled with POWHEG, PYTHIA8 and CT10 PDFs [33]. The SM WH , ZH , and $t\bar{t}H$ processes producing $H \rightarrow ZZ^* \rightarrow 4\ell$ backgrounds are modeled with PYTHIA8 with CTEQ6L1 PDFs.

- (ii) SM ZZ^* production. The rate of this background is estimated using simulation normalized to the SM cross section at NLO. The $ZZ^* \rightarrow 4\ell$ background is modeled using simulated samples generated with POWHEG [65] and PYTHIA8 [35] for $q\bar{q} \rightarrow ZZ^*$, and $ggZZ$ [66] and JIMMY [67] for $gg \rightarrow ZZ^*$, and CT10 PDFs for both.
- (iii) Z + jets and $t\bar{t}$. The rates of these background processes are estimated using data-driven methods. However Monte Carlo (MC) simulation is used to understand the systematic uncertainty on the data-driven techniques. The Z + jets production is modeled with up to five partons using ALPGEN [68] and is divided into two sources: Z + light-jets, which includes $Zc\bar{c}$ in the massless c -quark approximation and $Zb\bar{b}$ with $b\bar{b}$ from parton showers; and $Zb\bar{b}$ using matrix-element calculations that take into account the b -quark mass. The matching scheme of matrix elements and parton shower evolution (see Ref. [69] and the references therein) is used to remove any double counting of identical jets produced via the matrix-element calculation and the parton shower, but this scheme is not implemented for b -jets. Therefore, $b\bar{b}$ pairs with separation $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.4$ between the b -quarks are taken from the matrix-element calculation, whereas for $\Delta R < 0.4$ the parton-shower $b\bar{b}$ pairs are used. For comparison between data and simulation, the NNLO QCD FEWZ [70,71] and NLO QCD MCFM [72,73] cross-section calculations are used to normalize the simulations for inclusive Z boson and $Zb\bar{b}$ production, respectively. The $t\bar{t}$ background is simulated with MC@NLO-4.06 [74] with parton showers and underlying-event modeling as

implemented in HERWIG 6.5.20 [75] and JIMMY. The AUET2C [76] tune for the underlying events is used for $t\bar{t}$ with CT10 PDFs.

- (iv) SM WZ and WW production. The rates of these backgrounds are normalized to theoretical calculations at NLO in perturbative QCD [77]. The simulated event samples are produced with SHERPA [78] and CT10 PDFs.
- (v) Backgrounds containing J/ψ and Υ , namely ZJ/ψ and $Z\Upsilon$. These backgrounds are normalized using the ATLAS measurements described in Ref. [79]. These processes are modeled with PYTHIA8 [35] and CTEQ6L1 PDFs.

Differing pileup conditions (multiple proton-proton interactions in the same or neighboring bunch crossings) as a function of the instantaneous luminosity are taken into account by overlaying simulated minimum-bias events generated with PYTHIA8 onto the hard-scattering process and reweighting them according to the distribution of the mean number of interactions observed in data. The MC generated samples are processed either with a full ATLAS detector simulation [80] based on the GEANT4 program [81] or a fast simulation based on the parametrization of the response to the electromagnetic and hadronic showers in the ATLAS calorimeters [82] and a detailed simulation of other parts of the detector and the trigger system. The results based on the fast simulation are validated against fully simulated samples and the difference is found to be negligible. The simulated events are reconstructed and analyzed with the same procedure as the data, using the same trigger and event selection criteria.

IV. EVENT RECONSTRUCTION

A combination of single-lepton and dilepton triggers is used to select the data samples. The single-electron trigger has a transverse energy (E_T) threshold of 25 GeV while the single-muon trigger has a transverse momentum (p_T) threshold of 24 GeV. The dielectron trigger has a threshold of $E_T = 12$ GeV for both electrons. In the case of muons, triggers with symmetric thresholds at $p_T = 13$ GeV and asymmetric thresholds at 18 and 8 GeV are used. Finally, electron-muon triggers are used with electron E_T thresholds of 12 or 24 GeV depending on the electron identification requirement, and a muon p_T threshold of 8 GeV. The trigger efficiency for events passing the final selection is above 97% [39] in each of the final states considered.

Data events recorded during periods when significant portions of the relevant detector subsystems were not fully functional are rejected. These requirements are applied independently of the lepton final state. Events in a time window around a noise burst in the calorimeter are removed [83]. Further, all triggered events are required to contain a reconstructed primary vertex formed from at least three tracks, each with $p_T > 0.4$ GeV.

Electron candidates consist of clusters of energy deposited in the electromagnetic calorimeter and associated with ID tracks [84]. The clusters matched to tracks are required to satisfy a set of identification criteria such that the longitudinal and transverse shower profiles are consistent with those expected from electromagnetic showers. The electron transverse momentum is computed from the cluster energy and the track direction at the interaction point. Selected electrons must satisfy $E_T > 7$ GeV and $|\eta| < 2.47$. Each electron must have a longitudinal impact parameter (z_0) of less than 10 mm with respect to the reconstructed primary vertex, defined as the vertex with at least three associated tracks for which the $\sum p_T^2$ of the associated tracks is the highest. Muon candidates are formed by matching reconstructed ID tracks with either complete or partial tracks reconstructed in the muon spectrometer [85]. If a complete track is present, the two independent momentum measurements are combined; otherwise the momentum is measured using the ID. The muon reconstruction and identification coverage is extended by using tracks reconstructed in the forward region ($2.5 < |\eta| < 2.7$) of the MS, which is outside the ID coverage. In the center of the barrel region ($|\eta| < 0.1$), where there is no coverage from muon chambers, ID tracks with $p_T > 15$ GeV are identified as muons if their calorimetric energy deposits are consistent with a minimum ionizing particle. Only one muon per event is allowed to be reconstructed in the MS only or identified with the calorimeter. Selected muons must satisfy $p_T > 6$ GeV and $|\eta| < 2.7$. The requirement on the longitudinal impact parameter is the same as for electrons except for the muons reconstructed in the forward region without an ID track. To reject cosmic-ray muons, the impact parameter in the bending plane (d_0) is required to be within 1 mm of the primary vertex.

In order to avoid double-counting of leptons, an overlap removal procedure is applied. If two reconstructed electron candidates share the same ID track or are too close to each other in η and ϕ ($\Delta R < 0.1$), the one with the highest transverse energy deposit in the calorimeter is kept. An electron within $\Delta R = 0.2$ of a muon candidate is removed, and a calorimeter-based reconstructed muon within $\Delta R = 0.2$ of an electron is removed.

Once the leptons have been selected with the aforementioned basic identification and kinematic requirements, events with at least four selected leptons are kept. All possible combinations of four leptons (quadruplets) containing two same-flavor, opposite-charge sign (SFOS) leptons, are made. The selected leptons are ordered by decreasing transverse momentum and the three highest- p_T leptons should have, respectively, $p_T > 20$ GeV, $p_T > 15$ GeV and $p_T > 10$ GeV. It is then required that one (two) leptons match the single-lepton (dilepton) trigger objects. The leptons within each quadruplet are then ordered in SFOS pairs, and denoted 1 to 4, indices 1 and 2 being for the first pair, 3 and 4 for the second pair.

V. $H \rightarrow ZZ_d \rightarrow 4\ell$

A. Search strategy

The $H \rightarrow ZZ_d \rightarrow 4\ell$ search is conducted with the same sample of selected 4ℓ events as used in Refs. [26,27] with the four-lepton invariant mass requirement of $115 < m_{4\ell} < 130$ GeV. This collection of events is referred to as the 4ℓ sample. The invariant mass of the opposite-sign, same-flavor pair closest to the Z-boson pole mass of 91.2 GeV [86] is denoted m_{12} . The invariant mass of the remaining dilepton pair is defined as m_{34} . The $H \rightarrow 4\ell$ yield, denoted $n(H \rightarrow 4\ell)$, is determined by subtracting the relevant backgrounds from the 4ℓ sample as shown in Eq. (1):

$$n(H \rightarrow 4\ell) = n(4\ell) - n(ZZ^*) - n(t\bar{t}) - n(Z + \text{jets}). \quad (1)$$

The other backgrounds from WW , WZ , ZJ/ψ and ZY are negligible and not considered.

The search is performed by inspecting the m_{34} mass spectrum and testing for a local excess consistent with the decay of a narrow Z_d resonance. This is accomplished through a template fit of the m_{34} distribution, using histogram-based templates of the $H \rightarrow ZZ_d \rightarrow 4\ell$ signal and backgrounds. The signal template is obtained from simulation and is described in Sec. VB. The m_{34} distributions and the expected normalizations of the $t\bar{t}$ and $Z + \text{jets}$ backgrounds, along with the m_{34} distributions of the $H \rightarrow ZZ^* \rightarrow 4\ell$ background, as shown in Fig. 1, are determined as described in Sec. VD. The prefit signal and $H \rightarrow ZZ^* \rightarrow 4\ell$ background event yields are set equal to the $H \rightarrow 4\ell$ observed yield given by Eq. (1). The expected yields for the 4ℓ sample are shown in Table I.

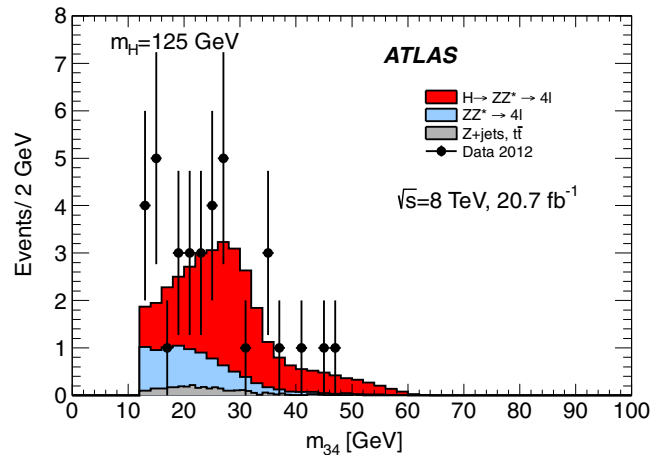


FIG. 1 (color online). The distribution of the mass of the second lepton pair, m_{34} , of the $\sqrt{s} = 8$ TeV data (filled circles with error bars) and the expected (prefit) backgrounds. The $H \rightarrow ZZ^* \rightarrow 4\ell$ expected (prefit) normalization, for a mass hypothesis of $m_H = 125$ GeV, is set by subtracting the expected contributions of the ZZ^* , $Z + \text{jets}$ and $t\bar{t}$ backgrounds from the total number of observed 4ℓ events in the data.

TABLE I. The estimated prefit background yields of (MC) ZZ^* , (data-driven) $t\bar{t} + Z + \text{jets}$, their sum, the observed 4ℓ event yield and the estimated prefit $H \rightarrow 4\ell$ contribution in the 4ℓ sample. The $H \rightarrow 4\ell$ estimate in the last column is obtained as the difference between the observed event yield and the sum of the ZZ^* and $t\bar{t} + Z + \text{jets}$ backgrounds. The prefit $H \rightarrow ZZ^* \rightarrow 4\ell$ background and $H \rightarrow ZZ_d \rightarrow 4\ell$ signal events are normalized to the $H \rightarrow 4\ell$ observed events. The uncertainties are statistical and systematic, respectively. The systematic uncertainties are discussed in Sec. V E. Uncertainties on the $H \rightarrow 4\ell$ rates do not include the statistical uncertainty from the observed number.

Channel	ZZ^*	$t\bar{t} + Z + \text{jets}$	Sum	Observed	$H \rightarrow 4\ell$
4μ	$3.1 \pm 0.02 \pm 0.4$	$0.6 \pm 0.04 \pm 0.2$	$3.7 \pm 0.04 \pm 0.6$	12	$8.3 \pm 0.04 \pm 0.6$
$4e$	$1.3 \pm 0.02 \pm 0.5$	$0.8 \pm 0.07 \pm 0.4$	$2.1 \pm 0.07 \pm 0.9$	9	$6.9 \pm 0.07 \pm 0.9$
$2\mu 2e$	$1.4 \pm 0.01 \pm 0.3$	$1.2 \pm 0.10 \pm 0.4$	$2.6 \pm 0.10 \pm 0.6$	7	$4.4 \pm 0.10 \pm 0.6$
$2e 2\mu$	$2.1 \pm 0.02 \pm 0.3$	$0.6 \pm 0.04 \pm 0.2$	$2.7 \pm 0.10 \pm 0.5$	8	$5.3 \pm 0.04 \pm 0.5$
all	$7.8 \pm 0.04 \pm 1.2$	$3.2 \pm 0.1 \pm 1.0$	$11.1 \pm 0.1 \pm 1.8$	36	$24.9 \pm 0.1 \pm 1.8$

In the absence of any significant local excess, the search can be used to constrain a relative branching ratio R_B , defined as

$$R_B = \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow 4\ell)} = \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell) + \text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)}, \quad (2)$$

where R_B is zero in the Standard Model. A likelihood function (\mathcal{L}) is defined as a product of Poisson probability densities (\mathcal{P}) in each bin (i) of the m_{34} distribution, and is used to obtain a measurement of R_B :

$$\mathcal{L}(\rho, \mu_H, \nu) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(n_i^{\text{obs}} | n_i^{\text{exp}}) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(n_i^{\text{obs}} | \mu_H \times (n_i^{Z^*} + \rho \times n_i^{Z_d}) + b_i(\nu)), \quad (3)$$

where μ_H is the normalization of the $H \rightarrow ZZ^* \rightarrow 4\ell$ background (and allowed to float in the fit), ρ the parameter of interest related to the $H \rightarrow ZZ_d \rightarrow 4\ell$ normalization and $\rho \times \mu_H$ the normalization of the $H \rightarrow ZZ_d \rightarrow 4\ell$ signal. The symbol ν represents the systematic uncertainties on the background estimates that are treated as nuisance parameters, and N_{bins} the total number of bins of the m_{34} distribution. The likelihood to observe the yield in some bin, n_i^{obs} , given the expected yield n_i^{exp} is then a function of the expected yields $n(H \rightarrow 4\ell)$ of $H \rightarrow ZZ_d \rightarrow 4\ell$ ($\mu_H \times \rho \times n_i^{Z_d}$) and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\mu_H \times n_i^{Z^*}$), and the contribution of backgrounds $b_i(\nu)$.

An upper bound on ρ is obtained from the binned likelihood fit to the data, and used in Eq. (2) to obtain a measurement of R_B , taking into account the detector acceptance (\mathcal{A}) and reconstruction efficiency (ϵ):

$$R_B = \frac{\rho \times \mu_H \times n(H \rightarrow 4\ell)}{\rho \times \mu_H \times n(H \rightarrow 4\ell) + C \times \mu_H \times n(H \rightarrow 4\ell)} = \frac{\rho}{\rho + C}, \quad (4)$$

where C is the ratio of the products of the acceptances and reconstruction efficiencies in $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ events:

$$C = \frac{\mathcal{A}_{ZZ_d} \times \epsilon_{ZZ_d}}{\mathcal{A}_{ZZ^*} \times \epsilon_{ZZ^*}}. \quad (5)$$

The acceptance is defined as the fraction of generated events that are within a fiducial region. The reconstruction efficiency is defined as the fraction of events within the fiducial region that are reconstructed and selected as part of the 4ℓ signal sample.

B. Signal modeling

A signal would produce a narrow peak in the m_{34} mass spectrum. The width of the m_{34} peak for the Z_d signal is dominated by detector resolution for all Z_d masses considered. For the individual decay channels and their combination, the resolutions of the m_{34} distributions are determined from Gaussian fits. The m_{34} resolutions show a linear trend between $m_{Z_d} = 15$ GeV and $m_{Z_d} = 55$ GeV and vary from 0.3 to 1.5 GeV, respectively, for the combination of all the final states. The resolutions of the m_{34} distributions are smaller than the mass spacing between the generated signal samples (5 GeV), requiring an interpolation to probe intermediate values of m_{Z_d} . Histogram-based templates are used to model the Z_d signal where no simulation is available; these templates are obtained from morphed signals produced with the procedure defined in Ref. [87]. The morphed signal templates are generated with a mass spacing of 1 GeV.

The acceptances and reconstruction efficiencies of the $H \rightarrow ZZ_d \rightarrow 4\ell$ signal and $H \rightarrow ZZ^* \rightarrow 4\ell$ background are used in Eqs. (4) and (5) to obtain the measurement of the relative branching ratio R_B . The acceptances and

efficiencies are derived with $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ MC samples where the Higgs boson is produced via ggF. The product of acceptance and reconstruction efficiency for VBF differs from ggF by only 1.2% and the contribution of VH and $t\bar{t}H$ production modes is negligible: the products of acceptance and reconstruction efficiency obtained using the ggF production mode are used also for VBF, VH and $t\bar{t}H$.

C. Event selection

The Higgs boson candidate is formed by selecting two pairs of SFOS leptons. The value of m_{12} is required to be between 50 and 106 GeV. The value of m_{34} is required to be in the range $12 \text{ GeV} \leq m_{34} \leq 115 \text{ GeV}$. The four-lepton invariant mass $m_{4\ell}$ is required to be in the range $115 < m_{4\ell} < 130 \text{ GeV}$. After applying the selection to the 8 TeV data sample, 36 events are left as shown in Table I. The events are grouped into four channels based on the flavor of the reconstructed leptons. Events with four electrons are in the $4e$ channel. Events in which the Z boson is reconstructed with electrons, and m_{34} is formed from muons, are in the $2e2\mu$ channel. Similarly, events in which the Z is reconstructed from muons and m_{34} is formed from electrons are in the $2\mu 2e$ channel. Events with four muons are in the 4μ channel.

D. Background estimation

The search is performed using the same background estimation strategy as the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements. The expected rates of the $t\bar{t}$ and $Z + \text{jets}$ backgrounds are estimated using data-driven methods as described in detail in Refs. [26,27]. The results of the expected $t\bar{t}$ and $Z + \text{jets}$ background estimations from data control regions are

TABLE II. Summary of the estimated expected numbers of $Z + \text{jets}$ and $t\bar{t}$ background events for the 20.7 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$ for the full mass range after kinematic selections, for the $H \rightarrow ZZ_d \rightarrow 4\ell$ search. The first uncertainty is statistical while the second is systematic. The uncertainties are given on the event yields. Approximately 80% of the $t\bar{t}$ and $Z + \text{jets}$ backgrounds have $m_{4\ell} < 160 \text{ GeV}$.

Method	Estimated background
4μ	
m_{12} fit: $Z + \text{jets}$ contribution	$2.4 \pm 0.5 \pm 0.6$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03$
$2e2\mu$	
m_{12} fit: $Z + \text{jets}$ contribution	$2.5 \pm 0.5 \pm 0.6$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02$
$2\mu 2e$	
$\ell\ell + e^\pm e^\mp$ relaxed requirements:	$5.2 \pm 0.4 \pm 0.5$
sum of $Z + \text{jets}$ and $t\bar{t}$ contributions	
$4e$	
$\ell\ell + e^\pm e^\mp$ relaxed requirements:	$3.2 \pm 0.5 \pm 0.4$
sum of $Z + \text{jets}$ and $t\bar{t}$ contributions	

TABLE III. The relative systematic uncertainties on the event yields in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search.

Systematic uncertainties (%)				
Source	4μ	$4e$	$2\mu 2e$	$2e2\mu$
Electron identification	...	9.4	8.7	2.4
Electron energy scale	...	0.4	...	0.2
Muon identification	0.8	...	0.4	0.7
Muon momentum scale	0.2	...	0.1	...
Luminosity	3.6	3.6	3.6	3.6
$t\bar{t}$ and $Z + \text{jets}$ normalization	25.0	25.0	25.0	25.0
ZZ^* (QCD scale)	5.0	5.0	5.0	5.0
ZZ^* ($q\bar{q}$ /PDF and α_s)	4.0	4.0	4.0	4.0
ZZ^* (gg/PDF and α_s)	8.0	8.0	8.0	8.0

summarized in Table II. In the “ m_{12} fit method,” the m_{12} distribution of $t\bar{t}$ is fitted with a second-order Chebychev polynomial, and the $Z + \text{jets}$ component is fitted with a Breit-Wigner line shape convolved with a Crystal Ball resolution function [26]. In the “ $\ell\ell + e^\pm e^\mp$ relaxed requirements” method, a background control region is formed by relaxing the electron selection criteria for electrons of the subleading pairs [26]. Since a fit to the data using m_{34} background templates is carried out in the search, both the distribution in m_{34} and normalization of the backgrounds are relevant. For all relevant backgrounds ($H \rightarrow ZZ^* \rightarrow 4\ell$, ZZ^* , $t\bar{t}$ and $Z + \text{jets}$) the m_{34} distribution is obtained from simulation.

E. Systematic uncertainties

The sources of the systematic uncertainties in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search are the same as in the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurements. Uncertainties on the lepton reconstruction and identification efficiencies, as well as on the energy and momentum reconstruction and scale are described in detail in Refs. [26,27], and shown in Table III. The lepton identification is the dominant contribution to the systematic uncertainties on the ZZ^* background. The largest uncertainty in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search is the normalization of the $t\bar{t}$ and $Z + \text{jets}$ backgrounds. Systematic uncertainties related to the determination of selection efficiencies of isolation and impact parameters requirements are shown to be negligible in comparison with other systematic uncertainties. The uncertainty in luminosity [28] is applied to the ZZ^* background normalization. The electron energy scale uncertainty is determined from $Z \rightarrow ee$ samples and for energies below 15 GeV from $J/\psi \rightarrow ee$ decays [26,27]. Final-state QED radiation modeling and background contamination affect the mass scale uncertainty negligibly. The muon momentum scale systematic uncertainty is determined from $Z \rightarrow \mu\mu$ samples and from $J/\psi \rightarrow \mu\mu$ as well as $\Upsilon \rightarrow \mu\mu$ decays [26,27]. Theory related systematic uncertainties on the Higgs production cross section and branching ratios are discussed in Refs. [39–41], but do not apply in this search since the

$H \rightarrow 4\ell$ normalization is obtained from data. Uncertainties on the m_{34} shapes arising from theory uncertainties on the PDFs and renormalization and factorization scales are found to be negligible. Theory cross-section uncertainties are applied to the ZZ^* background. Normalization uncertainties are taken into account for the $Z + \text{jets}$ and $t\bar{t}$ backgrounds based on the data-driven determination of these backgrounds.

F. Results and interpretation

A profile-likelihood test statistic is used with the CL_s modified frequentist formalism [88–91] implemented in the RooStats framework [92] to test whether the data are compatible with the signal-plus-background and background-only hypotheses. Separate fits are performed for different m_{Z_d} hypotheses from 15 to 55 GeV, with 1 GeV spacing. After scanning the m_{34} mass spectrum for an excess consistent with the presence of an $H \rightarrow ZZ_d \rightarrow 4\ell$ signal, no significant deviation from SM expectations is observed.

The asymptotic approximation [90] is used to estimate the expected and observed exclusion limits on ρ for the combination of all the final states, and the result is shown in Fig. 2. The relative branching ratio R_B as a function of m_{Z_d} is extracted using Eqs. (2) and (4) where the value of C as a function of m_{34} is shown in Fig. 3, for the combination of all four final states. This is then used with ρ to constrain the value of R_B , and the result is shown in Fig. 4 for the combination of all four final states.

The simplest benchmark model adds to the SM Lagrangian [6–8,10] a $U(1)_d$ gauge symmetry that introduces the dark vector boson Z_d . The dark vector boson may

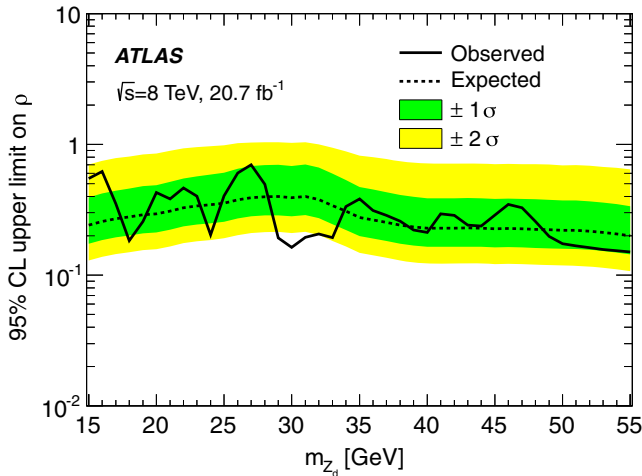


FIG. 2 (color online). The observed (solid line) and median expected (dashed line) 95% confidence level (C.L.) upper limits on the parameter ρ related to the $H \rightarrow ZZ_d \rightarrow 4\ell$ normalization as a function of m_{Z_d} , for the combination of all four channels (4μ , $4e$, $2\mu 2e$, $2e2\mu$). The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

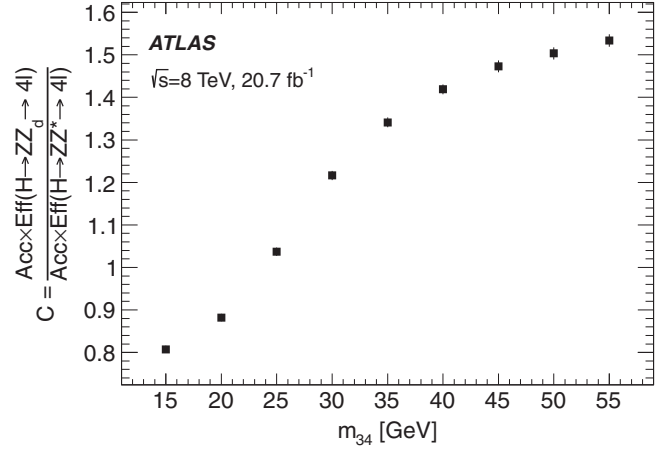


FIG. 3. The ratio C of the products of the acceptances and reconstruction efficiencies in $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ events as a function of m_{34} .

mix kinetically with the SM hypercharge gauge boson with kinetic mixing parameter ϵ [6,10]. This enables the decay $H \rightarrow ZZ_d$ through the hypercharge portal. The Z_d is assumed to be narrow and on shell. Furthermore, the present search assumes prompt Z_d decays consistent with current bounds on ϵ from electroweak constraints [18,19]. The coupling of the Z_d to SM fermions is given in Eq. (47) of Ref. [6] to be linear in ϵ , so that $\text{BR}(Z_d \rightarrow \ell\ell)$ is independent of ϵ due to cancellations [6]. In this model, the $H \rightarrow ZZ_d \rightarrow 4\ell$ search can be used to constrain the hypercharge kinetic mixing parameter ϵ as follows: the upper limit on R_B shown in Fig. 4 leads to an upper limit on $\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)$ assuming the SM branching ratio of $H \rightarrow ZZ^* \rightarrow 4\ell$ of 1.25×10^{-4} [40,41] as shown in Fig. 5. The limit on ϵ can be obtained directly from the $\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)$ upper bounds and by using Table 2

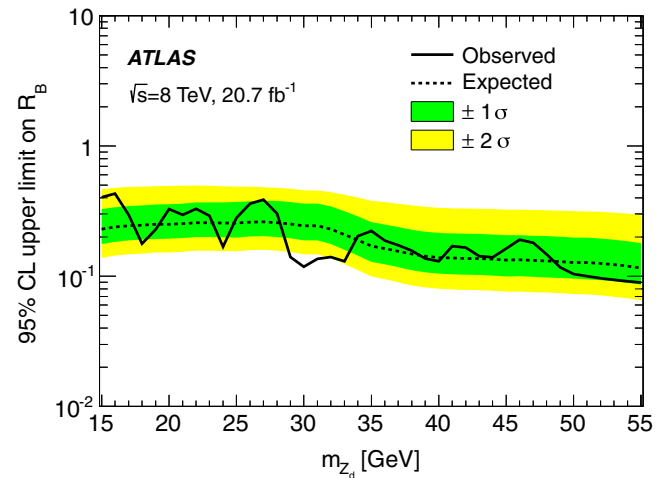


FIG. 4 (color online). The 95% C.L. upper limits on the relative branching ratio, $R_B = \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow 4\ell)}$ as a function of m_{Z_d} . The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

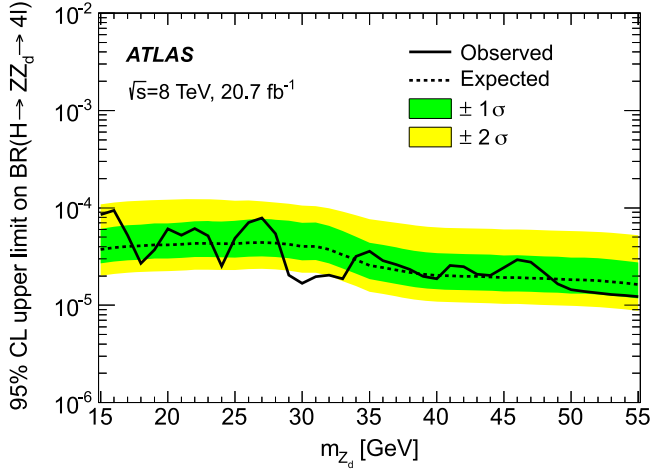


FIG. 5 (color online). The 95% C.L. upper limits on the branching ratio of $H \rightarrow ZZ_d \rightarrow 4\ell$ as a function of m_{Z_d} using the combined upper limit on R_B and the SM branching ratio of $H \rightarrow ZZ^* \rightarrow 4\ell$.

of Ref. [5]. The 95% C.L. upper bounds on ϵ are shown in Fig. 6 as a function of m_{Z_d} in the case $\epsilon \gg \kappa$ where κ is the Higgs portal coupling.

The measurement of the relative branching ratio R_B as shown in Fig. 4 can also be used to constrain the mass-mixing parameter of the model described in Refs. [7,8] where the SM is extended with a dark vector boson and another Higgs doublet, and a mass mixing between the dark vector boson and the SM Z boson is introduced. This model explores how a $U(1)_d$ gauge interaction in the hidden sector may manifest itself in the decays of the Higgs boson. The model also assumes that the Z_d , being in the hidden sector, does not couple directly to any SM particles including the Higgs boson (i.e. the SM particles do not carry dark charges). However, particles in the extensions to

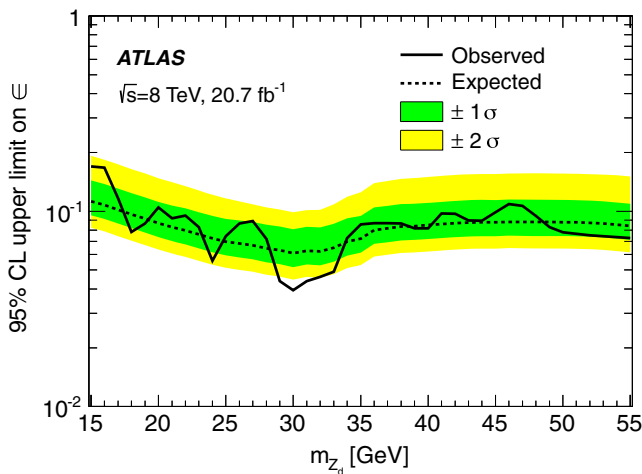


FIG. 6 (color online). The 95% C.L. upper limits on the gauge kinetic mixing parameter ϵ as a function of m_{Z_d} using the combined upper limit on the branching ratio of $H \rightarrow ZZ_d \rightarrow 4\ell$ and Table 2 of Ref. [5].

the SM, such as a second Higgs doublet, may carry dark charges allowing for indirect couplings via the Z - Z_d mass mixing. The possibility of mixing between the SM Higgs boson with other scalars such as the dark sector Higgs boson is not considered for simplicity. The Z - Z_d mass-mixing scenario also leads to potentially observable $H \rightarrow ZZ_d \rightarrow 4\ell$ decays at the LHC even with the total integrated luminosity collected in Run 1. The partial widths of $H \rightarrow ZZ_d \rightarrow 4\ell$ and $H \rightarrow ZZ_d$ are given in terms of the Z - Z_d mass-mixing parameter δ and m_{Z_d} in Eq. (34) of Ref. [8] and Eq. (A.4) of Ref. [7], respectively. As a result, using the measurement of the relative branching ratio R_B described in this paper, one may set upper bounds on the product $\delta^2 \times \text{BR}(Z_d \rightarrow 2\ell)$ as a function of m_{Z_d} as follows. From Eq. (2) and for $m_{Z_d} < (m_H - m_Z)$

$$\begin{aligned} \frac{\text{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)} &= \frac{R_B}{(1 - R_B)}, \\ &\simeq \frac{\Gamma(H \rightarrow ZZ_d)}{\Gamma_{\text{SM}}} \\ &\quad \times \frac{\text{BR}(Z^* \rightarrow 2\ell) \times \text{BR}(Z_d \rightarrow 2\ell)}{\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)}, \end{aligned} \quad (6)$$

where Γ_{SM} is the total width of the SM Higgs boson and $\Gamma(H \rightarrow ZZ_d) \ll \Gamma_{\text{SM}}$. From Eqs. (4), (A.3) and (A.4) of Ref. [7], $\Gamma(H \rightarrow ZZ_d) \sim \delta^2$. It therefore follows from Eq. (6), with the further assumption $m_{Z_d}^2 \ll (m_H^2 - m_Z^2)$ that

$$\begin{aligned} \frac{R_B}{(1 - R_B)} &\simeq \delta^2 \times \text{BR}(Z_d \rightarrow 2\ell) \\ &\quad \times \frac{\text{BR}(Z^* \rightarrow 2\ell)}{\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)} \times \frac{f(m_{Z_d})}{\Gamma_{\text{SM}}}, \\ f(m_{Z_d}) &= \frac{1}{16\pi} \frac{(m_H^2 - m_Z^2)^3}{v^2 m_H^3}, \end{aligned} \quad (7)$$

where v is the vacuum expectation value of the SM Higgs field. The limit is set on the product $\delta^2 \times \text{BR}(Z_d \rightarrow 2\ell)$ since both δ and $\text{BR}(Z_d \rightarrow 2\ell)$ are model dependent: in the case where kinetic mixing dominates, $\text{BR}(Z_d \rightarrow 2\ell) \sim 30\%$ for the model presented in Ref. [6] but it could be smaller when Z - Z_d mass mixing dominates [8]. In the m_{Z_d} mass range of 15 GeV to $(m_H - m_Z)$, the upper bounds on $\delta^2 \times \text{BR}(Z_d \rightarrow 2\ell)$ are in the range $\sim (1.5\text{--}8.7) \times 10^{-5}$ as shown in Fig. 7, assuming the same signal acceptances shown in Fig. 3.

VI. $H \rightarrow Z_d Z_d \rightarrow 4\ell$

A. Search strategy

$H \rightarrow Z_d Z_d \rightarrow 4\ell$ candidate events are selected as discussed in Sec. VI B. The Z , J/ψ , Υ vetoes are applied as

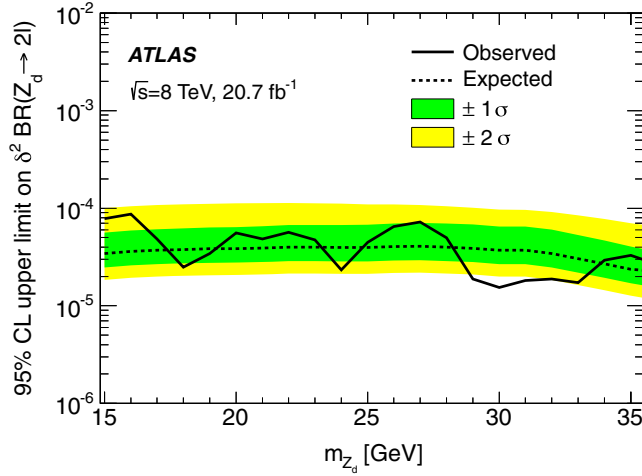


FIG. 7 (color online). The 95% C.L. upper limits on the product of the mass-mixing parameter δ and the branching ratio of Z_d decays to two leptons (electrons, or muons), $\delta^2 \times \text{BR}(Z_d \rightarrow 2\ell)$, as a function of m_{Z_d} using the combined upper limit on the relative branching ratio of $H \rightarrow ZZ_d \rightarrow 4\ell$ and the partial width of $H \rightarrow ZZ_d$ computed in Refs. [7,8].

also discussed in Sec. VI B. Subsequently, the analysis exploits the small mass difference between the two SFOS lepton pairs of the selected quadruplet to perform a counting experiment. After the small mass difference requirements between the SFOS lepton pairs, the estimated background contributions, coming from $H \rightarrow ZZ^* \rightarrow 4\ell$ and $ZZ^* \rightarrow 4\ell$, are small. These backgrounds are normalized with the theoretical calculations of their cross sections. The other backgrounds are found to be negligible. Since there is no significant excess, upper bounds on the signal strength, defined as the ratio of the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ rate normalized to the SM $H \rightarrow ZZ^* \rightarrow 4\ell$ expectation are set as a function of the hypothesized m_{Z_d} . In a benchmark model where the SM is extended with a dark vector boson and a dark Higgs boson, the measured upper bounds on the signal strength are used to set limits on the branching ratio of $H \rightarrow Z_d Z_d$ and on the Higgs boson mixing parameter as a function of m_{Z_d} [5,6].

B. Event selection

For the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search, unlike in the $H \rightarrow ZZ^* \rightarrow 4\ell$ study [93], there is no distinction between a primary pair (on-shell Z) and a secondary pair (off-shell Z), since both Z_d bosons are considered to be on shell. Among all the different quadruplets, only one is selected by minimizing the mass difference $\Delta m = |m_{12} - m_{34}|$ where m_{12} and m_{34} are the invariant masses of the first and second pairs, respectively. The mass difference Δm is expected to be minimal for the signal since the two dilepton systems should have invariant masses consistent with the same m_{Z_d} . No requirement is made on Δm ; it is used only to select a unique quadruplet with the smallest Δm . Subsequently,

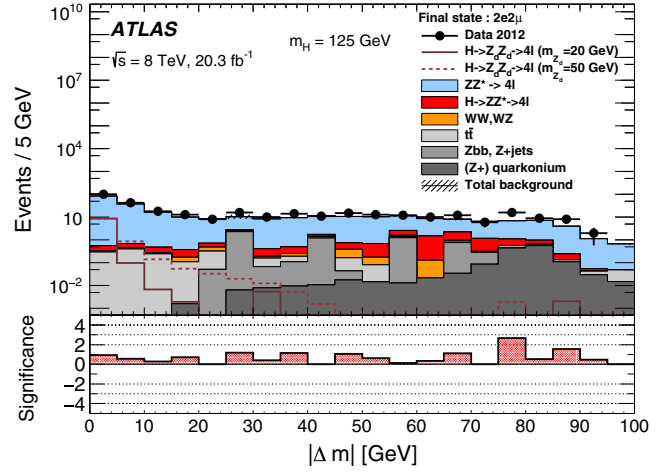


FIG. 8 (color online). Absolute mass difference between the two dilepton pairs, $\Delta m = |m_{12} - m_{34}|$ in the $2e2\mu$ channel, for $m_H = 125$ GeV. The shaded area shows both the statistical and systematic uncertainties. The bottom plot shows the significance of the observed number of events in the data compared to the expected number of events from the backgrounds. These distributions are obtained after the impact parameter significance requirements.

isolation and impact parameter significance requirements are imposed on the leptons of the selected quadruplet as described in Ref. [39]. Figure 8 shows the minimal value of Δm for the $2e2\mu$ final state after the impact parameter significance requirements. Similar distributions are found for the $4e$ and 4μ final states. The dilepton and four-lepton invariant mass distributions are shown in Figs. 9 and 10, respectively, for m_{12} and m_{34} combined.

For the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search with hypothesized m_{Z_d} , after the impact parameter significance requirements on the selected leptons, four final requirements are applied:

- (1) $115 < m_{4\ell} < 130$ GeV where $m_{4\ell}$ is the invariant mass of the four leptons in the quadruplet, consistent with the mass of the discovered Higgs boson of about 125 GeV [94].
- (2) Z , J/ψ , and Υ vetoes on all SFOS pairs in the selected quadruplet. The Z veto discards the event if either of the dilepton invariant masses is consistent with the Z -boson pole mass: $|m_{12} - m_Z| < 10$ GeV or $|m_{34} - m_Z| < 10$ GeV. For the J/ψ and Υ veto, the dilepton invariant masses are required to be above 12 GeV. This requirement suppresses backgrounds with Z bosons, J/ψ , and Υ .
- (3) The loose signal region requirement: $m_{12} < m_H/2$ and $m_{34} < m_H/2$, where $m_H = 125$ GeV. In the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search, the kinematic limit for on-shell Z_d is $m_{Z_d} < m_H/2$.
- (4) The tight signal region requirement: $|m_{Z_d} - m_{12}| < \delta m$ and $|m_{Z_d} - m_{34}| < \delta m$. The optimized values of the δm requirements are 5/3/4.5 GeV for the $4e/4\mu/2e2\mu$ final states, respectively (the δm

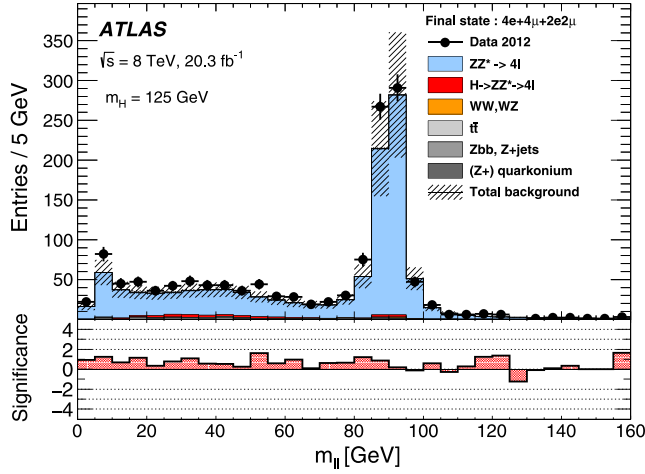


FIG. 9 (color online). Dilepton invariant mass, $m_{\ell\ell} \equiv m_{12}$ or m_{34} , in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed number of events in the data compared to the expected number of events from the backgrounds. These distributions are obtained after the impact parameter significance requirement.

requirement varies with the hypothesized m_{Z_d} but the impact of the variation is negligible). This requirement suppresses the backgrounds further by restricting the search region to within δm of the hypothesized m_{Z_d} .

These requirements (1)–(4) define the signal region (SR) of $H \rightarrow Z_d Z_d \rightarrow 4\ell$ that is dependent on the hypothesized

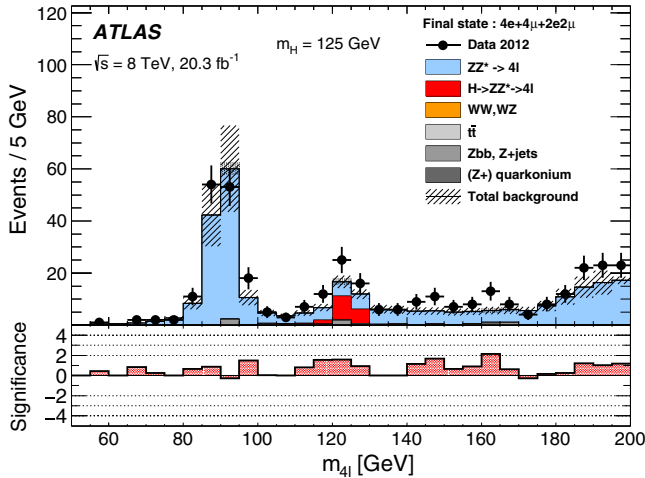


FIG. 10 (color online). Four-lepton invariant mass, in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed number of events in the data compared to the expected number of events from the backgrounds. These distributions are obtained after the impact parameter significance requirement.

m_{Z_d} , and is essentially background-free, but contains small estimated background contributions from $H \rightarrow ZZ^* \rightarrow 4\ell$ and $ZZ^* \rightarrow 4\ell$ processes as shown in Sec. VIE.

C. Background estimation

For the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search, the main background contributions in the signal region come from the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $ZZ^* \rightarrow 4\ell$ processes. These backgrounds are suppressed by the requirements of the tight signal region, as explained in Sec. VIB. Other backgrounds with smaller contributions come from the $Z + \text{jets}$ and $t\bar{t}$, WW and WZ processes as shown in Fig. 11. The $H \rightarrow ZZ^* \rightarrow 4\ell$, $ZZ^* \rightarrow 4\ell$, WW and WZ backgrounds are estimated from simulation and normalized with theoretical calculations of their cross sections. After applying the tight signal region requirements described in Sec. VIB, the $Z + \text{jets}$, $t\bar{t}$ and diboson backgrounds are negligible. In the case where the Monte Carlo calculation yields zero expected background events in the tight signal region, an upper bound at 68% C.L. on the expected events is estimated using 1.14 events [86], scaled to the data luminosity and normalized to the background cross section:

$$N_{\text{background}} < L \times \sigma \times \left(\frac{1.14}{N_{\text{tot}}} \right), \quad (8)$$

where L is the total integrated luminosity, σ the cross section of the background process, and N_{tot} the total

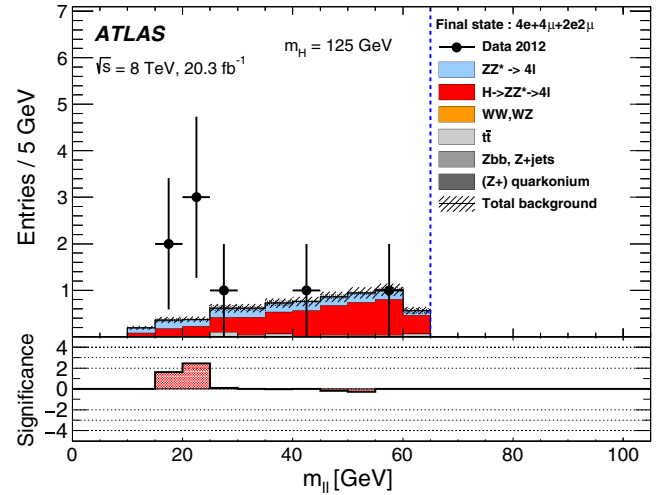


FIG. 11 (color online). Dilepton invariant mass, $m_{\ell\ell} \equiv m_{12}$ or m_{34} after the loose signal region requirements described in Sec. VIB for the $4e$, 4μ and, $2e2\mu$ final states combined, for $m_H = 125$ GeV. The data is represented by the black dots, and the backgrounds are represented by the filled histograms. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed data events compared to the expected number of events from the backgrounds. The dashed vertical line is the kinematic limit (m_{12} or $m_{34} < 63$ GeV) of the loose signal region requirements as discussed in Sec. VIB.

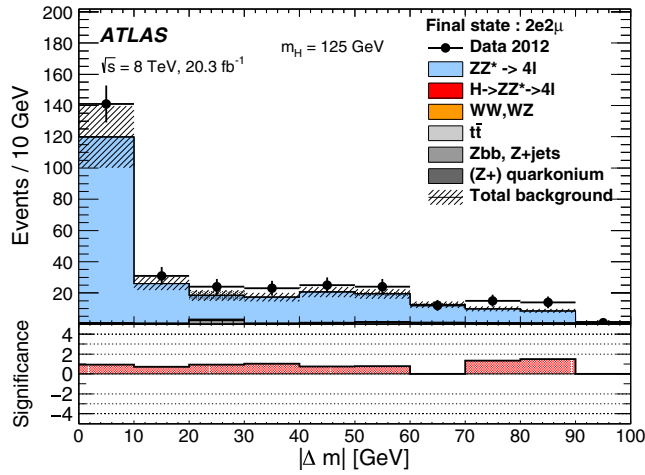


FIG. 12 (color online). The minimal absolute mass difference for the $2e2\mu$ final state. Events are selected after the impact parameter significance requirement and $m_{4\ell} \notin (115, 130)$ GeV. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the measured number of events in the data compared to the estimated number of events from the backgrounds.

number of weighted events simulated for the background process.

To validate the background estimation, a signal depleted control region is defined by reversing the four-lepton invariant mass requirement with an $m_{4\ell} < 115$ GeV or $m_{4\ell} > 130$ GeV requirement. Good agreement between expectation and observation is found in this validation control region as shown in Fig. 12.

D. Systematic uncertainties

The systematic uncertainties on the theoretical calculations of the cross sections used in the event selection and identification efficiencies are taken into account. The effects of PDFs, α_s , and renormalization and factorization scale uncertainties on the total inclusive cross sections for the Higgs production by ggF, VBF, VH and $t\bar{t}H$ are obtained from Refs. [40,41]. The renormalization, factorization scales and PDFs and α_s uncertainties are applied to the ZZ^* background estimates. The uncertainties due to the limited number of MC events in the $t\bar{t}$, $Z + \text{jets}$, ZJ/ψ , ZY and WW/WZ background simulations are estimated as described in Sec. VIC. The luminosity uncertainty [28] is applied to all signal yields, as well as to the background yields that are normalized with their theory cross sections. The detector systematic uncertainties due to uncertainties in the electron and muon identification efficiencies are estimated within the acceptance of the signal region requirements. There are several components to these uncertainties. For the muons, uncertainties in the reconstruction and identification efficiency, and in the momentum resolution and scale, are included. For the electrons, uncertainties in the reconstruction and identification efficiency, the

TABLE IV. The relative systematic uncertainties on the event yields in the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search.

Systematic uncertainties (%)			
Source	4μ	$4e$	$2e2\mu$
Electron identification	...	6.7	3.2
Electron energy scale	...	0.8	0.3
Muon identification	2.6	...	1.3
Muon momentum scale	0.1	...	0.1
Luminosity	2.8	2.8	2.8
ggF QCD	7.8	7.8	7.8
ggF PDFs and α_s	7.5	7.5	7.5
ZZ^* Normalization	5.0	5.0	5.0

isolation and impact parameter significance requirements, and the energy scale and energy resolution are considered. The systematic uncertainties are summarized in Table IV.

E. Results and interpretation

Figures 11 and 13 show the distributions of the dilepton invariant mass (for m_{12} and m_{34} combined) and the absolute mass difference $\Delta m = |m_{12} - m_{34}|$ after the loose signal region requirements. Four data events pass the loose signal region requirements, one in the $4e$ channel, two in the 4μ channel and one in the $2e2\mu$ channel. Two of these four events pass the tight signal region requirements: the event in the $4e$ channel and one of the events in the 4μ channel. The event in the $4e$ channel has dilepton masses of 21.8 and 28.1 GeV as shown in Fig. 11, and is consistent with a Z_d

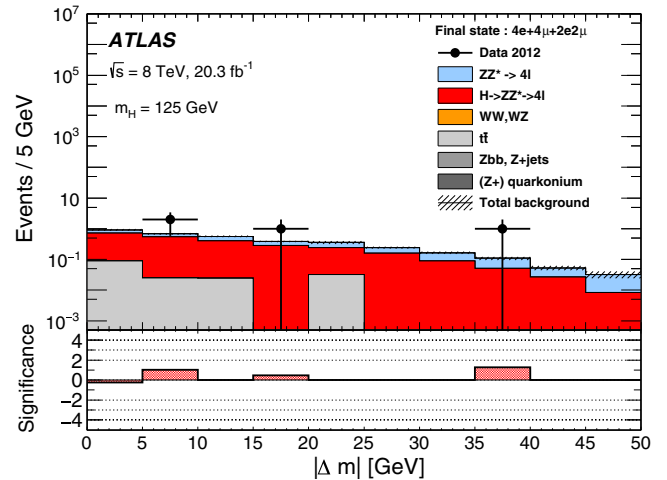


FIG. 13 (color online). Absolute mass difference, $\Delta m = |m_{12} - m_{34}|$ after the loose signal region requirements described in Sec. VIB for the $4e$, 4μ and, $2e2\mu$ final states combined, for $m_H = 125$ GeV. The data is represented by the black dots, and the backgrounds are represented by the filled histograms. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed data events compared to the expected number of events from the backgrounds.

mass in the range $23.5 \leq m_{Z_d} \leq 26.5$ GeV. For the event in the 4μ channel that passes the tight signal region requirements, the dilepton invariant masses are 23.2 and 18.0 GeV as shown in Fig. 11, and they are consistent with a Z_d mass in the range $20.5 \leq m_{Z_d} \leq 21.0$ GeV. In the m_{Z_d} range of 15 to 30 GeV where four data events pass the loose signal region requirements, histogram interpolation [87] is used in steps of 0.5 GeV to obtain the signal acceptances and efficiencies at the hypothesized m_{Z_d} . The expected numbers of signal, background and data events, after applying the tight signal region requirements, are shown in Table V.

For each m_{Z_d} , in the absence of any significant excess of events consistent with the signal hypothesis, the upper limits are computed from a maximum-likelihood fit to the numbers of data and expected signal and background events in the tight signal regions, following the CL_s modified frequentist formalism [88,89] with the profile-likelihood test statistic [90,91]. The nuisance parameters associated with the systematic uncertainties described in Sec. VID are profiled. The parameter of interest in the fit is the signal strength μ_d defined as the ratio of the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ rate relative to the SM $H \rightarrow ZZ^* \rightarrow 4\ell$ rate:

$$\mu_d = \frac{\sigma \times \text{BR}(H \rightarrow Z_d Z_d \rightarrow 4\ell)}{[\sigma \times \text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)]_{\text{SM}}}. \quad (9)$$

The systematic uncertainties in the electron and muon identification efficiencies, renormalization and factorization scales and PDF are 100% correlated between the signal

and backgrounds. Pseudoexperiments are used to compute the 95% C.L. upper bound μ_d in each of the final states and their combination, and for each of the hypothesized m_{Z_d} . The 95% confidence level upper bounds on the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ rates are shown in Fig. 14 relative to the SM Higgs boson process $H \rightarrow ZZ^* \rightarrow 4\ell$ as a function of the hypothesized m_{Z_d} for the combination of the three final states $4e$, $2e2\mu$ and 4μ . Assuming the SM Higgs boson production cross section and using $\text{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)_{\text{SM}} = 1.25 \times 10^{-4}$ [40,41], upper bounds on the branching ratio of $H \rightarrow Z_d Z_d \rightarrow 4\ell$ can be obtained from Eq. (9), as shown in Fig. 15.

The simplest benchmark model is the SM plus a dark vector boson and a dark Higgs boson as discussed in Refs. [6,10], where the branching ratio of $Z_d \rightarrow \ell\ell$ is given as a function of m_{Z_d} . This can be used to convert the measurement of the upper bound on the signal strength μ_d into an upper bound on the branching ratio $\text{BR}(H \rightarrow Z_d Z_d)$ assuming the SM Higgs boson production cross section. Figure 16 shows the 95% C.L. upper limit on the branching ratio of $H \rightarrow Z_d Z_d$ as a function of m_{Z_d} using the combined μ_d of the three final states. The weaker bound at higher m_{Z_d} is due to the fact that the branching ratio $Z_d \rightarrow \ell\ell$ drops slightly at higher m_{Z_d} [6] as other decay channels become accessible. The $H \rightarrow Z_d Z_d$ decay can be used to obtain an m_{Z_d} -dependent limit on a Higgs mixing parameter κ' [6]:

$$\kappa' = \kappa \times \frac{m_H^2}{[m_H^2 - m_S^2]}, \quad (10)$$

TABLE V. The expected and observed numbers of events in the tight signal region of the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search for each of the three final states, for the hypothesized mass $m_{Z_d} = 25$ and 20.5 GeV. Statistical and systematic uncertainties are given respectively for the signal and the background expectations. One event in data passes all the selections in the $4e$ channel and is consistent with $23.5 \leq m_{Z_d} \leq 26.5$ GeV. One other data event passes all the selections in the 4μ channel and is consistent with $20.5 \leq m_{Z_d} \leq 21.0$ GeV. The $H \rightarrow ZZ^* \rightarrow 4\ell$ numbers are summed over the ggF, VBF, ZH, WH and $t\bar{t}H$ processes.

Process	$4e$	4μ	$2e2\mu$
$H \rightarrow ZZ^* \rightarrow 4\ell$	$(1.5 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(1.0 \pm 0.3 \pm 0.3) \times 10^{-2}$	$(2.9 \pm 1.0 \pm 2.0) \times 10^{-3}$
$ZZ^* \rightarrow 4\ell$	$(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$	$(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$	$(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z + jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ ψ and ZY	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
Total background	$< 5.6 \times 10^{-2}$	$< 5.9 \times 10^{-2}$	$< 5.3 \times 10^{-2}$
Data	1	0	0
$H \rightarrow ZZ^* \rightarrow 4\ell$	$(1.2 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(5.8 \pm 2.0 \pm 2.0) \times 10^{-3}$	$(2.6 \pm 1.0 \pm 0.2) \times 10^{-3}$
$ZZ^* \rightarrow 4\ell$	$(3.5 \pm 2.0 \pm 0.2) \times 10^{-3}$	$(4.1 \pm 2.7 \pm 0.2) \times 10^{-3}$	$(2.0 \pm 0.6 \pm 0.1) \times 10^{-2}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z + jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ ψ and ZY	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
Total background	$< 5.3 \times 10^{-2}$	$< 5.1 \times 10^{-2}$	$< 6.4 \times 10^{-2}$
Data	0	1	0

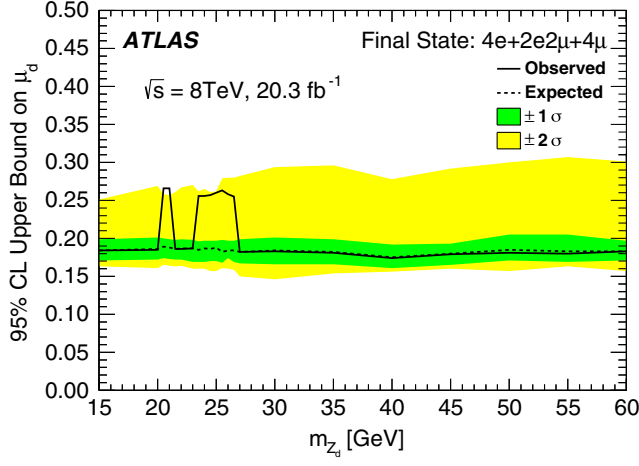


FIG. 14 (color online). The 95% confidence level upper bound on the signal strength $\mu_d = \frac{\sigma \times \text{BR}(H \rightarrow Z_d Z_d \rightarrow 4\ell)}{[\sigma \times \text{BR}(H \rightarrow Z Z^* \rightarrow 4\ell)]_{\text{SM}}}$ of $H \rightarrow Z_d Z_d \rightarrow 4\ell$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

where κ is the size of the Higgs portal coupling and m_S is the mass of the dark Higgs boson. The partial width of $H \rightarrow Z_d Z_d$ is given in terms of κ [5]. In the regime where the Higgs mixing parameter dominates ($\kappa \gg \epsilon$), $m_S > m_H/2$, $m_{Z_d} < m_H/2$ and $H \rightarrow Z_d Z^* \rightarrow 4\ell$ is negligible, the only relevant decay is $H \rightarrow Z_d Z_d$. Therefore the partial width $\Gamma(H \rightarrow Z_d Z_d)$ can be written as

$$\Gamma(H \rightarrow Z_d Z_d) = \Gamma_{\text{SM}} \frac{\text{BR}(H \rightarrow Z_d Z_d)}{1 - \text{BR}(H \rightarrow Z_d Z_d)}. \quad (11)$$

The Higgs portal coupling parameter κ is obtained using Eq. (53) of Ref. [6] or Table 2 of Ref. [5]:

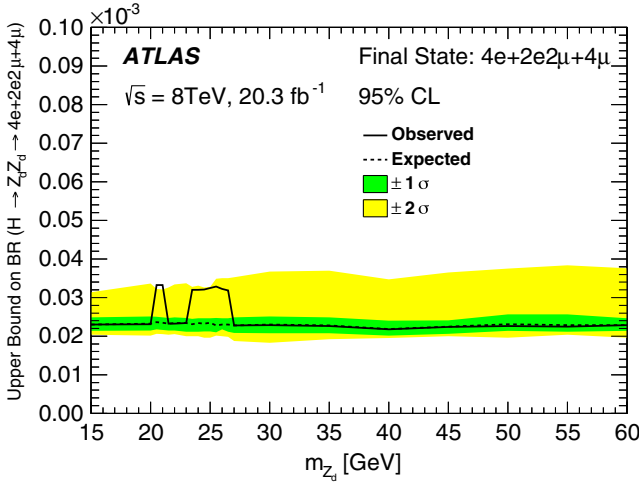


FIG. 15 (color online). The 95% confidence level upper bound on the branching ratio of $H \rightarrow Z_d Z_d \rightarrow 4\ell$ as a function of m_{Z_d} , in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

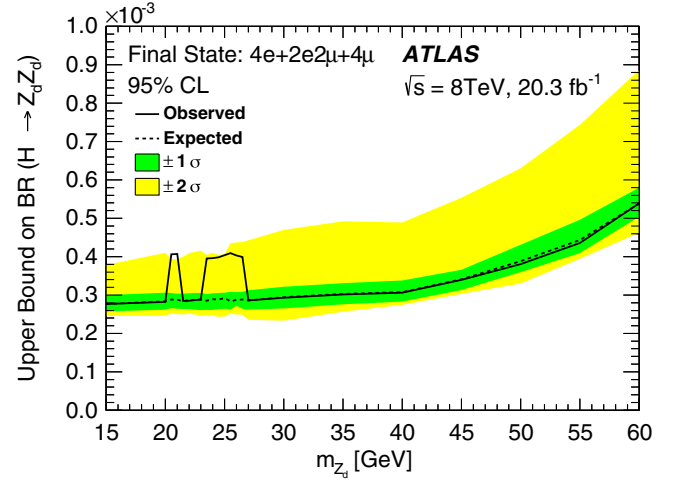


FIG. 16 (color online). The 95% confidence level upper bound on the branching ratio of $H \rightarrow Z_d Z_d$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

$$\kappa^2 = \frac{\Gamma_{\text{SM}}}{f(m_{Z_d})} \frac{\text{BR}(H \rightarrow Z_d Z_d)}{1 - \text{BR}(H \rightarrow Z_d Z_d)}, \quad (12)$$

where

$$f(m_{Z_d}) = \frac{v^2}{32\pi m_H} \times \sqrt{1 - \frac{4m_{Z_d}^2}{m_H^2}} \times \frac{(m_H^2 + 2m_{Z_d}^2)^2 - 8(m_H^2 - m_{Z_d}^2)m_{Z_d}^2}{(m_H^2 - m_S^2)^2}. \quad (13)$$

Figure 17 shows the upper bound on the effective Higgs mixing parameter as a function of m_{Z_d} ; for

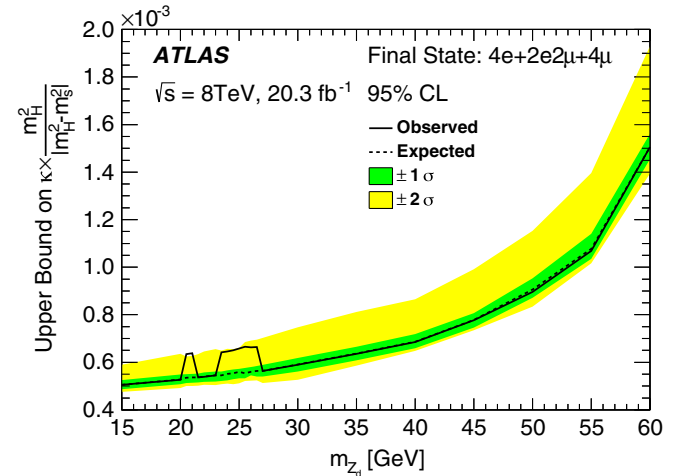


FIG. 17 (color online). The 95% confidence level upper bound on the Higgs mixing parameter $\kappa \times m_H^2 / |m_H^2 - m_S^2|$ as a function of m_{Z_d} , in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

$m_H/2 < m_S < 2m_H$, this would correspond to an upper bound on the Higgs portal coupling in the range $\kappa \sim (1-10) \times 10^{-4}$.

An interpretation for $H \rightarrow Z_d Z_d$ is not done in the $Z-Z_d$ mass mixing scenario described in Refs. [7,8] since in this model the rate of $H \rightarrow Z_d Z_d$ is highly suppressed relative to that of $H \rightarrow ZZ_d$.

VII. CONCLUSIONS

Two searches for an exotic gauge boson Z_d that couples to the discovered SM Higgs boson at a mass around 125 GeV in four-lepton events are presented, using the ATLAS detector at the LHC.

The $H \rightarrow ZZ_d \rightarrow 4\ell$ analysis uses the events resulting from Higgs boson decays to four leptons to search for an exotic gauge boson Z_d , by examining the m_{34} mass distribution. The results obtained in this search cover the exotic gauge boson mass range of $15 < m_{Z_d} < 55$ GeV, and are based on proton-proton collisions data at $\sqrt{s} = 8$ TeV with an integrated luminosity of 20.7 fb^{-1} . Observed and expected exclusion limits on the branching ratio of $H \rightarrow ZZ_d \rightarrow 4\ell$ relative to $H \rightarrow 4\ell$ are estimated for the combination of all the final states. For relative branching ratios above 0.4 (observed) and 0.2 (expected), the entire mass range of $15 < m_{Z_d} < 55$ GeV is excluded at 95% C.L. Upper bounds at 95% C.L. on the branching ratio of $H \rightarrow ZZ_d \rightarrow 4\ell$ are set in the range $(1-9) \times 10^{-5}$ for $15 < m_{Z_d} < 55$ GeV, assuming the SM branching ratio of $H \rightarrow ZZ^* \rightarrow 4\ell$.

The $H \rightarrow Z_d Z_d \rightarrow 4\ell$ search covers the exotic gauge boson mass range from 15 GeV up to the kinematic limit of $m_H/2$. An integrated luminosity of 20.3 fb^{-1} at 8 TeV is used in this search. One data event is observed to pass all the signal region selections in the $4e$ channel, and has dilepton invariant masses of 21.8 and 28.1 GeV. This $4e$ event is consistent with a Z_d mass in the range $23.5 < m_{Z_d} < 26.5$ GeV. Another data event is observed to pass all the signal region selections in the 4μ channel, and has dilepton invariant masses of 23.2 and 18.0 GeV. This 4μ event is consistent with a Z_d mass in the range $20.5 < m_{Z_d} < 21.0$ GeV. In the absence of a significant excess, upper bounds on the signal strength (and thus on the cross section times branching ratio) are set for the mass range of $15 < m_{Z_d} < 60$ GeV using the combined $4e$, $2e2\mu$, 4μ final states.

Using a simplified model where the SM is extended with the addition of an exotic gauge boson and a dark Higgs boson, upper bounds on the gauge kinetic mixing

parameter ϵ (when $\epsilon \gg \kappa$), are set in the range $(4-17) \times 10^{-2}$ at 95% C.L., assuming the SM branching ratio of $H \rightarrow ZZ^* \rightarrow 4\ell$, for $15 < m_{Z_d} < 55$ GeV. Assuming the SM Higgs production cross section, upper bounds on the branching ratio of $H \rightarrow Z_d Z_d$, as well as on the Higgs portal coupling parameter κ are set in the range $(2-3) \times 10^{-5}$ and $(1-10) \times 10^{-4}$, respectively, at 95% C.L., for $15 < m_{Z_d} < 60$ GeV.

Upper bounds on the effective mass-mixing parameter $\delta^2 \times \text{BR}(Z_d \rightarrow \ell\ell)$, resulting from the $U(1)_d$ gauge symmetry, are also set using the branching ratio measurements in the $H \rightarrow ZZ_d \rightarrow 4\ell$ search, and are in the range $(1.5-8.7) \times 10^{-5}$ for $15 < m_{Z_d} < 35$ GeV.

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